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In Situ and Satellite Surface Temperature Records in Antarctica

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ABSTRACT

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The objective of the study is to evaluate current and potential capabilities for monitoring surface temperatures in the Antarctic region. The results from the three most viable techniques are compared and the potential applications of each are investigated. The first technique is the oldest technique which makes use of thermistors installed in automated weather stations (AWS). These thermistors provide the highest accuracy (to a hundreth of a degree) and the best temporal resolution but the number of stations in which they are installed are very limited and therefore the network of stations provide very poor spatial coverage. Other problems with this technique include possible instrument hardware problems due to an extremely harsh environment and the possibility of the thermistors being covered by snow that would keep them from providing accurate surface temperatures. The second technique is the use of satellite infrared data. The data provides accurate measurements of the skin layer of the surface since the radiometers have high accuracies and the emissivity of the surface is well known and close to that of a blackbody. The problem with this technique is that the infrared radiation cannot penetrate clouds and when it is cloudy, the satellite sensor cannot see the surface. The temporal sampling is therefore uneven and because cloud covered surfaces tend to have different temperatures than cloud free surfaces, the standard monthly average products produced from this type of data, may have some bias. The third technique is the use of satellite passive microwave data. Passive microwave systems provide surface measurements for all times because they detect relatively long wavelengths of radiation that are least affected by atmospheric cloud particles. The penetration depths of these radiation in snow, however, can be substantial and of the order of several tens of centimeters over the Antarctic ice sheet. Spatial variability in the emissivity of the surface is therefore a problem and currently, they can produce surface temperatures only in places where there are already surface temperature measurements that can be used to calibrate the signal. The comparative analysis from this study shows that the three systems provide basically very similar seasonal temperature distribution of the surface in 5 study regions. The AWS and the infrared daily data are also shown to be coherent but there are times when the values would differ by as much as 17 °C, which may be when the cloud masking for the infrared sensor was not good. But on a monthly basis, the two systems agree to within about 3 °C. The passive microwave data do not provide the same daily fluctuation as the AWS and infrared data because the signal emanates primarily from the subsurface and snow is known to be a good insulator. The data, however, provide good continuous and consistent coverage and can be utilized to supplement the infrared date, especially in areas where there is persistent cloud cover. They also provide data at the AWS location even after the AWS thermistor is no longer functional. The AWS data, on the other hand, provides the standard that is needed to transform both satellite measurements into useful instruments, while at present, the infrared data provides good spatial coverage necessary for true global monitoring.

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INTRODUCTION

Detection of climate change involves determination of a multi-year baseline for a climate parameter and then detecting variations that exceed its observed range over the baseline period.

Increasing temperatures, possibly linked to global climate warming, have been detected at sites on the Antarctic Peninsula (Jacka and Budd, 1992; King, 1994; Vaughan and Doake, 1996). Further inland, at specific automatic weather stations (AWS), data on near-surface temperature (T_A) are beginning to define a climate baseline (Shuman and Stearns, 2001). However, these data have significant gaps and may not be representative of broader regional or continental-scale patterns. Temperature fields derived from satellite infrared (Comiso, 2000) or passive microwave sensors can provide a much more complete characterization of spatial and temporal variations in Antarctic temperature. Currently, the only spatially detailed record of surface temperature across Antarctica is provided by Advanced Very High Resolution Radiometer's (AVHRR) infrared channels (T_{IR}) but they must be carefully processed to remove the effects of clouds (Comiso, 2000). Passive microwave data from the 37 GHz channel of the Special Sensor Microwave/Imager (SSM/I) are not influenced by cloud-cover and can be calibrated (T_C) at specific AWS locations (Shuman et al., 1995) or by complex radiative transfer models (Fung and Chen, 1981; Comiso et al., 1982), but cannot yet be broadly extrapolated in space and time because of still poorly understood spatial variations in the emissivity of the surface. Time series of these satellite data, if they could be used consistently, would provide the needed temperature data to identify regional and continental-scale climate change across Antarctica. This study, using recently published temperature data, analyzes in situ and satellite temperature information and documents the advantages and limitations of each approach. The intent of this study is to use the AWS data to gain insight into the accuracy of the retrieved surface temperatures from satellite infrared and microwave data and establish confidence limits on these data.

This project used three types of temperature data from 1992 that were spatially- and temporally-coregistered: 1) daily-average T_A records from five AWS operated by the University of Wisconsin in Antarctica (see Figure 1 and Table 1); 2) daily-average AVHRR T_{IR} data compiled and processed as described in Comiso (2000); and 3) daily-average T_C data derived from the Special Sensor Microwave/Imager (SSM/I) data sets compiled by the National Snow and Ice Data Center (NSIDC) and calibrated as described in Shuman and Stearns (2001). The three measurements are not exactly for the same physical parameter since the AWS measures near-surface air temperature (~2m), the infrared sensor measures skin-depth temperature, and the passive microwave sensor measures the average temperature of the upper surface layer. This comparative analysis will help establish how the three data sets can be used in tandem to study the variations of an important climate parameter through time.

STATEMENT OF PROBLEM

Near-surface air temperature data have been consistently monitored by AWS since 1980 at some sites and many of these observations continue to the current day (Shuman and Stearns, 2001). However, as the data in Figure 2 illustrate, the records from Antarctic AWS sites are not continuous. Because of equipment and logistics challenges in this harsh environment, AWS records may be composed of segments that are separated by temporal gaps of considerable length. These data gaps complicate the effort of long-term in situ climate monitoring. In addition, AWS T_A data may not perfectly represent actual temperature at all times. For example, minor increases due to solar heating have been suggested at some ice sheet locations (Shuman et al., 2001). See Comiso (2000) for a detailed analysis of in situ temperature records from Antarctica sites.

AVHRR data have been available since the 1970s but it was not until 1981 that digital versions of continuous orbital data records became available. Their wide swath (2240 km) and a revisit time of about 102 minutes makes AVHRR data suitable for variability studies of surface temperatures at a reasonably good temporal resolution. For temperature studies, a large fraction of the data, however, has to be discarded because of cloud effects since infrared radiation cannot penetrate through the clouds. Nevertheless, because of a relatively high sampling rate, there is enough cloud-free surface data to cover the entire Antarctic region in a week. Weekly maps of the entire Antarctic region are thus possible to produce with the infrared data set but because of residuals in the cloud masking, these maps are not as accurate as the monthly maps where the averaging of more data points makes the impact of cloud contaminated pixels less prominent.

Passive microwave brightness temperatures (T_B) from Antarctica also begin in the 1970s, from 1978 onward consistently, and can be an effective surrogate temperature indicator over polar snow if they can be accurately calibrated into Tc values (see Figure 2). The T_B data do not provide a pure temperature signal however; it is a function of the characteristics of the snow and ice over the depth of emission (Shuman et al., 1995; Shuman and Stearns, 2001). This means that passive microwave data cannot be used directly to substitute for missing T_A or T_{IR} temperatures but must first be calibrated to account for approximately annual variations in snow emission characteristics. As discussed in Shuman et al. (1995), radiative transfer modeling will account for all the factors that influence the conversion of T_B data into temperature estimates. Currently however, field observations are required to account for variations in snow characteristics and thus this approach is not yet widely applicable. The temperature inferred from passive microwave data represents the average of a layer of snow that may vary in thickness from one location to another because of changes in snow properties. Depending on frequency, the penetration depth can be as deep as a few meters but is thought to be a few 10s of centimeters for the 37GHz channel used here (Shuman et al., 1995). An additional complication for the passive microwave technique is introduced by brief melt events in the vicinity of some Antarctica AWS (Zwally and Fiegles, 1994; Abdalati and Steffen, 1997). Large brightness temperature increases associated with the presence of liquid water do not significantly impact this analysis but they will be discussed later (see Figure 3 and associated dates in the AWS Lettau Tc record, Figure 2c).

METHODOLOGY

The AWS data were obtained from the 3-hourly files at the anonymous ftp site operated by the University of Wisconsin, Madison. These data are quality-controlled averages of 10-minute AWS observations that are also available from this site (ftp://ice.ssec.wisc.edu/). The daily-average T_A values are then derived from the 3-hourly data. Detailed information on the AWS units that are used here, including data transmission and quality control, is presented in Stearns et al. (1993) and Stearns and Weidner (1993). These papers specify the temperature resolution of the AWS sensors as 0.125°C. Absolute calibration in the longer term and adjustments to sensor height as snow accumulates remain problems for T_A data (Shuman and Stearns, 2001; Shuman et al., 2001).

The technique for using infrared data to obtain skin-depth temperature maps of the polar regions have been discussed previously (Steffen et al., 1993; Comiso, 2000). The key infrared sensor has been the Advanced Very High Resolution Radiometer (AVHRR) because of continuous and long-term coverage. The sensor has five channels from the visible to thermal infrared but it is the thermal channel at 11 μm that is used to estimate surface temperatures while the other channels are used for cloud masking and atmospheric correction. Also, clouds are especially difficult to discriminate from snow surfaces in the data and although a special masking technique has been used (Comiso, 2000) in addition to conventional techniques, some residuals remain. It is the latter that causes some of the errors in the daily data to be unusually high. However, because they occur in different places at different times, the impact on the accuracy of the monthly data, which is the standard climatology product (Genthon and Braun, 1995), is not as big because of the averaging period. The AVHRR data set used for this study is the Global Area Coverage (GAC) data set that has a resolution of 5 km by 3 km at nadir. The continuous orbital data set was acquired from the GSFC AVHRR Pathfinder Project that did much of the original quality control. The data was in turn mapped to polar stereographic maps similar to that used for passive microwave but at a resolution of 6.25 km.

The passive microwave data used here were extracted from National Snow and Ice Data Center CD-ROMs (NSIDC, 1992). Daily-averaged, 37 GHz, vertical polarization (V), brightness temperatures (T_B) from the Special Sensor Microwave/Imager (SSM/I-F11) for the 25 x 25 km grid cell covering each AWS site were compiled to document their multi-year "temperature" trends for each site. The South Pole record examined here cannot be studied by this technique, as it is not covered by passive microwave data (see Figure 3). Brightness temperature data from the 37 GHz V (0.81 cm wavelength) channel begin in 1978 and continue through the present day. The T_B measurement accuracy of the 37 GHz V channels on this instrument is ±2 K for the SSM/I (Hollinger et al., 1991). The 37 GHz V T_B data are calibrated using AWS air temperatures by an emissivity modeling technique (Shuman et al., 1995; Shuman and Stearns, 2001) to create the T_C time series to be compared to the T_A and T_{IR} data.

RESULTS AND DISCUSSION

The daily temperature plots (Figure 2) illustrate the challenge of interpreting temperature data from different data sets in Antarctica for just one year. Although each of the temperature records documents the same general annual trend, there are characteristics that need to be understood with each data set. The Byrd record is less than 50% complete for T_A and contains a several week period where T_{IR} appears to be too low (in late May to early June). The Clean Air site has a distinct offset between T_A and T_{IR} throughout the year as well as gaps in T_{IR}. The Lettau record has a roughly 3 month gap in T_A and the Siple record has less than a third of a year of T_A data (this AWS ceased operations in 1992). Only the Lynn record is substantially complete for 1992 but this AWS too is no longer operating (see Figure 1 and Table 1). For each site, the T_C data is complete (see Shuman and Stearns, 2001) but is considerably less variable due to its dependence on emission from the near surface snow. Incidentally, this analysis is arbitrarily focussed on 1992 largely because of the availability of daily T_{IR} data for that particular year (see Comiso, 2000 for details). Unfortunately, this focus on 1992 will limit to some extent the comparisons capable of being conducted from this data. Further work on additional years of data is planned to insure that the conclusions based on 1992 are representative.

The plots in Figure 4 illustrate the overall nature of the two satellite temperature records to the in situ measurements. Daily differences can be estimated visually from the plots in Figure 2. The satellite measurements necessarily cover a larger region (4 ~6x6km pixels for T_{IR} and a 25x25km pixel for T_C) than that measured by the "point source" AWS. Therefore, exact correspondence between the data sets is not likely. In general, the plots of Figure 4 shows that the T_{IR} data has a strong correlation with T_A as the majority of daily values fall in the ±10K range along the zero difference line. The same is true of the T_C data but with a tendency for these data to overestimate temperature at the low end of the data range. All averages discussed here are based on exactly corresponding dates. This means the data sets are as compatible as possible. Table 2 summarizes the daily temperature difference data.

With the exception of the period in late May and early June at Byrd where T_{IR} values are too low (Figure 4a), infrared temperature estimates track T_A closely at all the sites except Clean Air. The T_{IR} values there show a consistent offset with a mean difference value that is greater than 4K (Figure 4b). The offset is distinctly linear suggesting that it should be easy to compensate for in the AVHRR processing algorithm. Preliminary examination of the problem suggests it may be the result of the scan angle needed to retrieve data at this latitude. In general, data closer to nadir (± 48.5° instead of 55.4° needed to cover the South Pole) are used for temperature retrievals (Comiso, 2000). It should be noted that assigning the offset entirely to the infrared data assumes that there is nothing wrong with the AWS data which at times can have some problems (Shuman et al., 2001). Similarly, the Lynn data (Figure 4d) also show a small offset from T_A that suggests T_{IR} values here are apparently more than 1K too high. Overall, scatter in these data is likely a result of incomplete cloud masking and its daily magnitude is suggested by the standard deviation values shown in Figure 4. Averaging the daily data to derive monthly values diminishes the impact of any individual day's data (Comiso, 2000).

The T_{IR} values are thought to be too low during late May and early June at Byrd largely because the T_C values show a smaller but similar temperature trend as compared to T_A during this period. As noted above, the tendency for T_C data to overestimate temperature is illustrated by values plotting above even the upper diagonal lines at Byrd, Lettau, and Lynn (the T_A-T_C difference is negative). The scatter plots shown in Figure 4 also suggest a slight curvature (see Figure 4c for an example) that can be traced to the technique's tendency to slightly overestimate emissivity in the spring and fall and slightly underestimate it in the winter and summer (Shuman et al., 1995). The winter period seems to be the most significant at these sites for reasons which are not well understood but are probably related to the emissivity correction not being the simple sinusoid that is currently required by the technique.

The monthly difference plots (see Figure 5) show smaller means and standard deviations as discussed above. These plots give confidence that these temperature data can be used in climatological analyses (Genthon and Braun, 1995). All differences are within 5K of the zero line if the problematic period at Byrd is discounted and the offset is corrected at Clean Air in the T_{IR} data. The mean values for both T_A-T_{IR} and T_A-T_C are less than 1K at all sites except for the small T_{IR} offset previously noted at Lynn. The reasons for the offset at Lynn are unclear but may be due to the relatively steeper topography (in the immediate vicinity of the AWS, see Figure 1). In other words, the satellite view of the site may cover more variable topography than at the other AWS sites and the T_{IR} values may not as accurately match T_A as a result. Table 3 summarizes the monthly temperature difference data.

Because of the relatively short T_A records available for analysis at several of the AWS sites, annual mean comparisons with T_{IR} and T_C were not satisfactory representations of the true "annual" temperature. Consequently, annual means were calculated and differenced using the more complete T_{IR} and T_C values. This provides a more representative value and allows the uncertainty of these independent data sets to be conveniently evaluated (see Table 4). In all cases, the annual difference was under 1.5K. Note that the larger difference values at Byrd and Lynn include a period of problematic data and a distinct offset respectively. These annual difference values provide a confidence limit on annual average data derived from satellite sources that is compatible with those reported in Shuman and Stearns (Figure 10).

Comparative analysis has revealed unique characteristics and unexpected weaknesses of the satellite data sets. The daily infrared data show basically the same variability as the AWS data but there are times when the discrepancies are high. An examination of the values from individual orbits that went into the daily data indicate that there are times when some values are a few standard deviations away from the daily average. This is likely due to imperfections in the cloud masking technique but further studies are required especially through comparative analysis with the TERRA/MODIS (Moderate Resolution Imaging Spectroradiometer) data that may have the right set of channels for accurate cloud masking in the polar regions. The monthly averages, which is the final temperature product as reported by Comiso (2000), show better agreement with corresponding coastal AWS data but may be further improved through the use of an appropriate filtering technique. The daily microwave data show basically the same long-term variability as the AWS data but it does not capture short-term variability as well as the infrared data. This is likely associated with the microwave data representing an average temperature that is less responsive to short term fluctuations in atmospheric temperature. Because the snow surface is optically thin at microwave frequencies, the observed temperatures actually represent the average temperature of a layer of snow. And since snow is a good insulator, the short-term fluctuation of this layer may not be identical to that of the surface. However, temporal averages, starting with weekly averages of passive microwave data agree very well with both AWS data and infrared data. This makes the passive microwave a very useful data set for filling in gaps in both infrared and AWS data sets.

CONCLUSIONS

The significance of this study is that it enabled an improved understanding of three currently available Antarctic surface temperature data sets. At present, the thermal infrared data provide the only spatially detailed temperature distributions in Antarctica but there are gaps in the data because of intermittent cloud cover. The passive microwave data has the potential of providing spatially detailed, continuous, and gap-free temperature distributions but more research is needed to be able to correctly calibrate it to account for regional changes in the radiative characteristics of the snow cover. The AWS data provide the most accurate data but it is the most difficult to use for large-scale scientific research because of limited spatial coverage and gaps in the temporal series due to occasional instrument malfunction. The AWS data, however, provide the means to evaluate the value and the significance of both the infrared and the passive microwave data sets.

These different near-surface temperature data sets are quite complimentary and should enable development of improved temperature baselines in Antarctica. Although T_A data may be discontinuous, T_{IR} data can accurately fill most gaps at specific sites. Any gaps due to cloud cover in the T_{IR} record can then be filled with extrapolated T_C values and these values also provide a reliability check on the spatially more extensive T_{IR} data. Processing requirements are significant, especially for T_{IR} however, and detection and removal of cloud impacts and accurately calibrating these data remains a challenge. Overall, this study has demonstrated that the satellite data compare quite well in most cases assuming that these AWS T_A data reliably represent these locations. The limited comparisons presented here certainly justify continued efforts with additional years of data at these and other sites across the Antarctic continent. Although individual day differences between in situ and satellite temperatures can be quite large, the average errors are relatively small and appear well constrained. For the thermal infrared data set the standard products are the monthly averages which appear to provide a realistic representation of temperature distributions around the continent. Some of the discrepancies between the methods studied here are probably due to the differing spatial and temporal resolutions of the three different methods. We also have assumed that the AWS hardware for measuring temperature is always in perfect condition but this is not guaranteed in such an adverse environment and there may be some instances when the AWS actually provides erroneous results despite quality control procedures. For optimal accuracy, especially at high temporal resolution, a combination of the three methods may be necessary to determine the temperature histories sufficiently to accurately to determine climate baseline data and any potential changes to come.

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CAPTIONS FOR FIGURES

Figure 1 - Illustration of the locations and dates of operation of the five inland Antarctic automatic weather stations used in this study.

Figure 2 - Illustration of the daily-average AWS and multi-sensor satellite temperature data for 1992 used in this study (2a - AWS Byrd, 2b - AWS Clean Air, 2c - AWS Lettau, 2d - AWS Lynn, 2e - AWS Siple). All plots are presented with the same unit ranges for the x and y axes to aid comparison. Data gaps greater than 4 days are indicated for all records. Note the period during late May and early June at Byrd where T_{IR} departs from the other records. Also note the T_C "spike" associated with surface melt during the austral summer of 1991-1992 at Lettau, as well as the distinct offset between T_A and T_{IR} at AWS Clean Air.

Figure 3 - Illustration of the spatial extent of a melt event (lighter gray tones) that briefly impacts the Lettau T_C record. The event lasted from approximately 12/21/91 to 1/6/92 and reached its apparent maximum extent on 12/23/91 (illustrated). This daily average SSM/I 37 GHz horizontal polarization image also shows the coverage gap around South Pole and inconsistent data values associated with an isolated sensor sweep in East Antarctica.

Figure 4 - Scatter plots showing the resulting daily-average temperature differences (T_A-T_{IR} or T_A-T_C) for each site (4a - AWS Byrd, 4b - AWS Clean Air, 4c - AWS Lettau, 4d - AWS Lynn, 4e - AWS Siple). The outer diagonal lines across the plot represent ±10K differences and the centerline represents 0K difference. Note the high T_A-T_{IR} values for Byrd associated with the May-June divergence and the distinct offsets at Clean Air and Lynn as well as the calibration problems in the daily T_C temperatures (values well above the zero difference isotherm especially at lower temperatures indicating T_A-T_C is strongly negative).

Figure 5 - Scatter plots showing the resulting monthly-average temperature differences (T_A-T_{IR} or T_A-T_C) for each site (4a - AWS Byrd, 4b - AWS Clean Air, 4c - AWS Lettau, 4d - AWS Lynn, 4e - AWS Siple). Note the distinct offsets at Clean Air and Lynn. The outer diagonal lines across the plot represent ±5K differences and the centerline represents 0K difference.

Table 1 - Site data for inland Antarctic AWS temperature records[1].

AWS Name	Latitude	Longitude	Elevation (m)	Grid[2]	Start (m/y)	Stop (m/y)
Byrd	80.01°S	119.40°W	1530	121 196	2/80	
Clean Air	90.00°S	120.00°W	2835		1/86	
Lettau	82.52°S	174.45°W	55	155 206	1/86	
Lynn	74.21°S	160.41°E	1772	182 239	1/88	1/98
Siple	75.90°S	84.00°W	1054	97 168	1/82	4/92

[1]This analysis is based on available 3 hourly average data taken from the University of Wisconsin server in March 1999. [2]The grid column contains the coordinates of the 25km Special Sensor Microwave Imager (SSM/I) pixel covering the AWS location. Note that there is no SSM/I coverage at the South Pole where AWS Clean Air is located.

Table 2 - Difference statistics for all 1992 daily mean temperatures.

T_A-T_{IR}	Byrd	Clean Air	Lettau	Lynn	Siple
Difference	0.69	-4.38	-0.62	-1.12	-0.64
Days	151	305	235	324	97
T_A-T_C	Byrd	Clean Air	Lettau	Lynn	Siple
Difference	-0.18		-0.12	0.23	-0.38
Days	171		280	344	112

This analysis is based on all days where there was both an air temperature (T_A) and an AVHRR infrared temperature (T_{IR}) or a calibrated SSM/I temperature (T_C). Note that there is no T_C data for AWS Clean Air due to the hole in SSM/I coverage at the South Pole.

Table 3 - Difference statistics for all 1992 monthly mean temperatures.

T_A-T_{IR}	Byrd	Clean Air	Lettau	Lynn	Siple
Difference	0.64	-4.29	-0.57	-1.23	-0.59
Months	6	12	10	12	4

T_A-T_C	Byrd	Clean Air	Lettau	Lynn	Siple
Difference	-0.38		-0.12	0.12	-0.05
Months	6		10	12	4

This analysis is based on all days of a calendar month where there was both an air temperature (T_A) and an AVHRR infrared temperature (T_{IR}) or a calibrated SSM/I temperature (T_C). Note that there is no T_C data for AWS Clean Air due to the hole in SSM/I coverage at the South Pole.

Table 4 - Difference statistics for all 1992 T_{IR} and T_C daily mean temperatures.

	Byrd	Clean Air	Lettau	Lynn	Siple
Days	323	305	313	342	328
T_{IR}	245.66	226.38	246.97	238.85	248.12
T_C	247.02		246.64	237.64	247.61
T_{IR}-T_C	-1.36		0.33	1.21	0.52

This analysis is based on all days where there was both an AVHRR infrared temperature (T_{IR}) and a calibrated SSM/I temperature (T_C). Note that there is no T_C data for AWS Clean Air due to the hole in SSM/I coverage at the South Pole.

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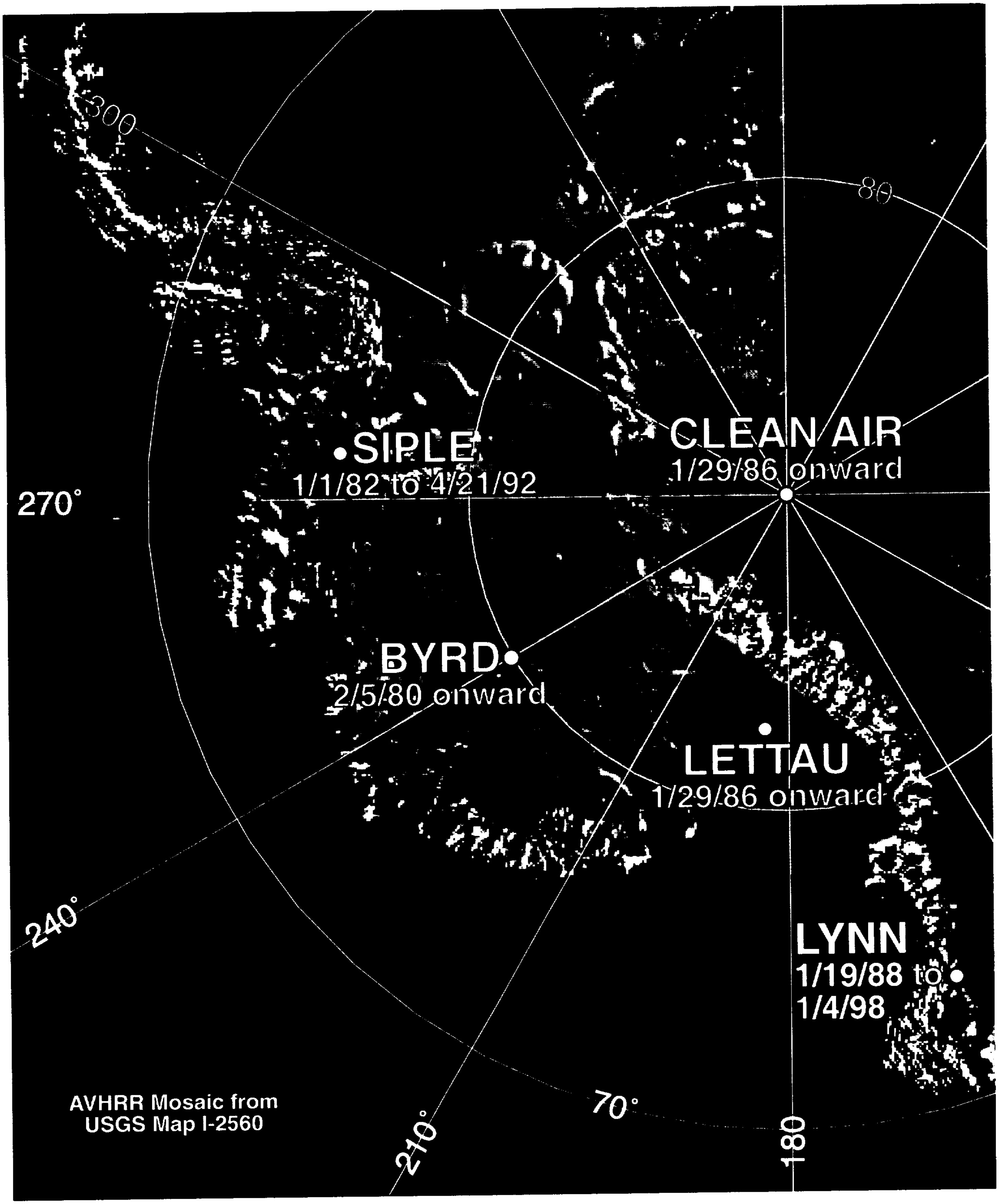
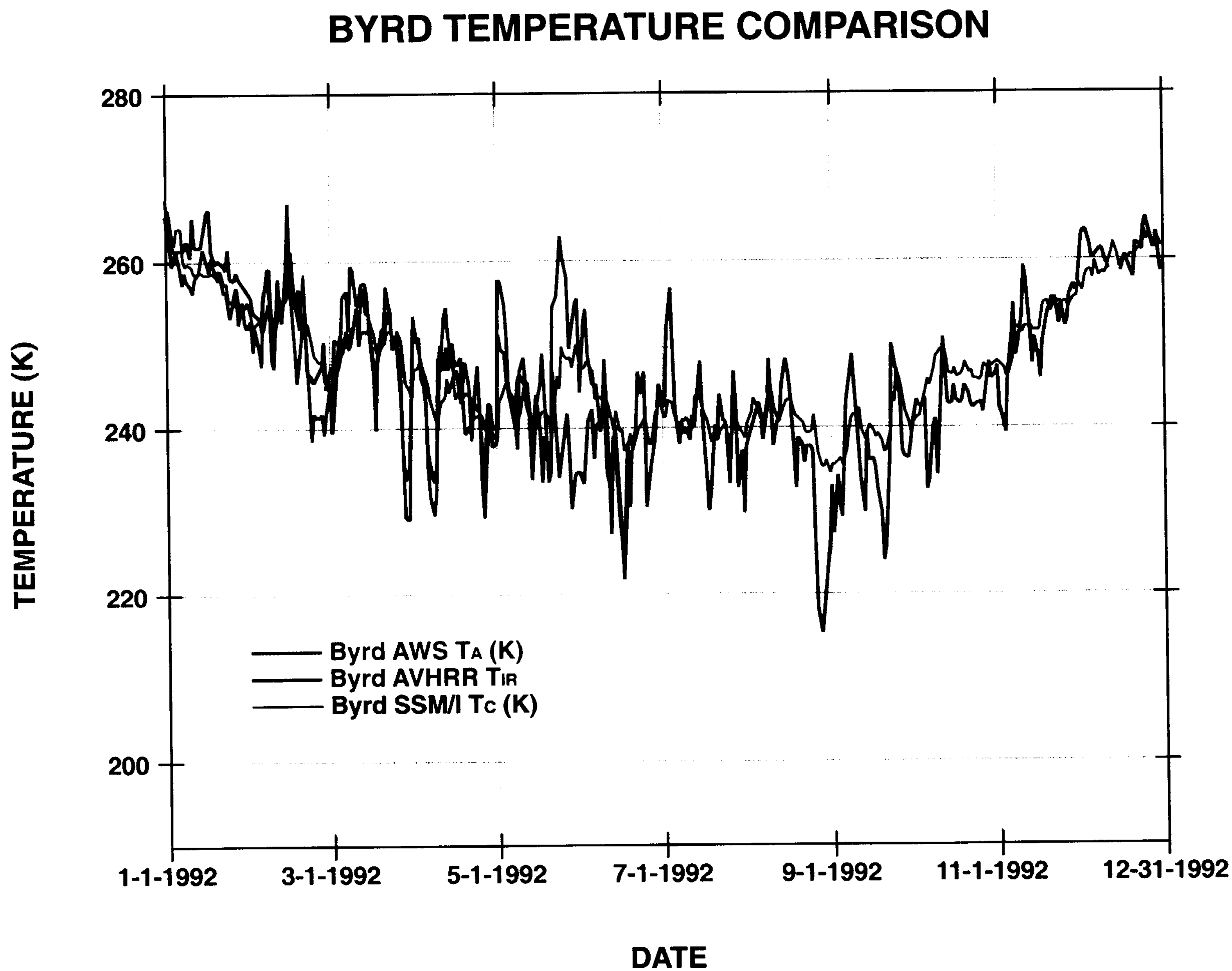


Figure 1, Shuman and Comiso



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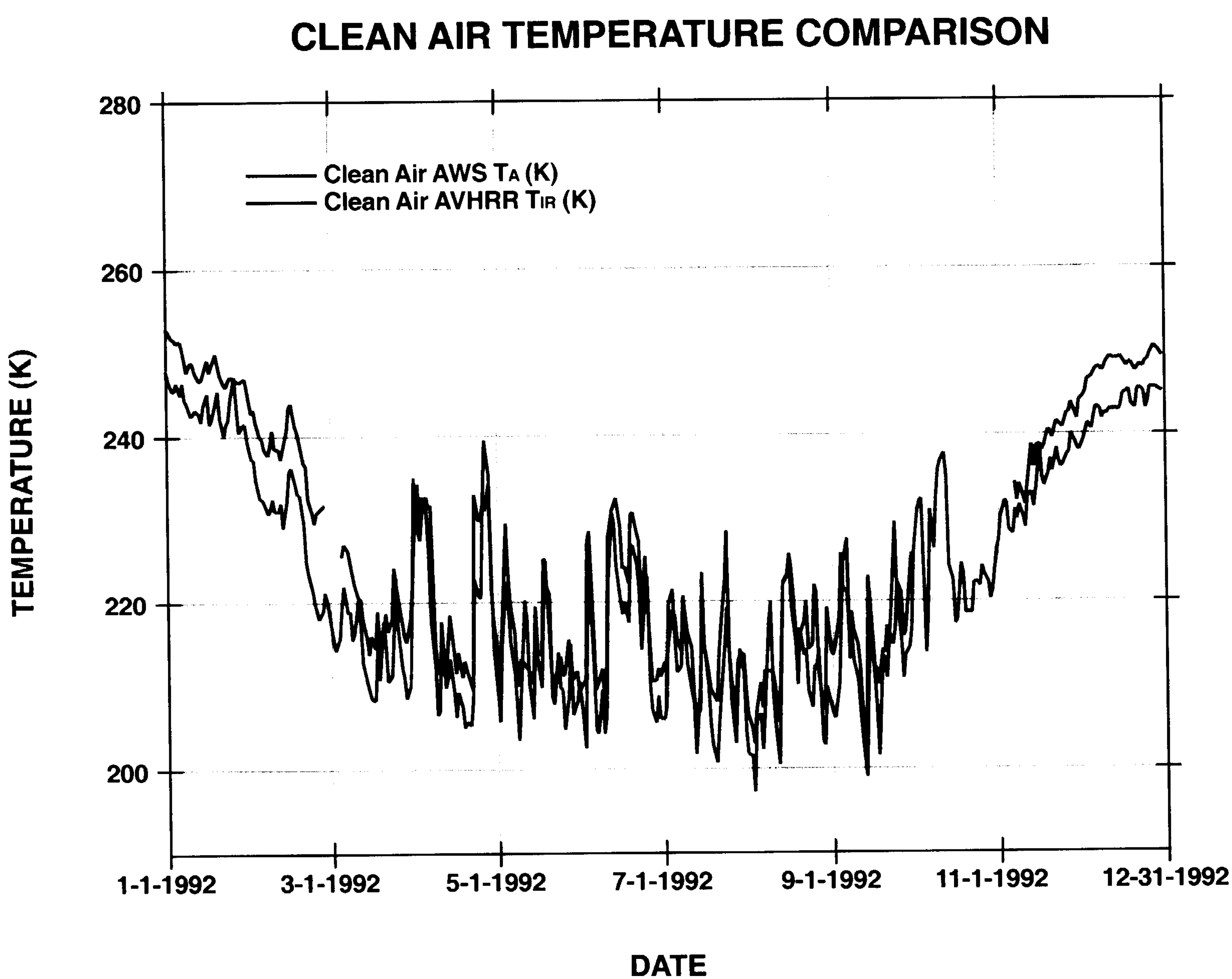

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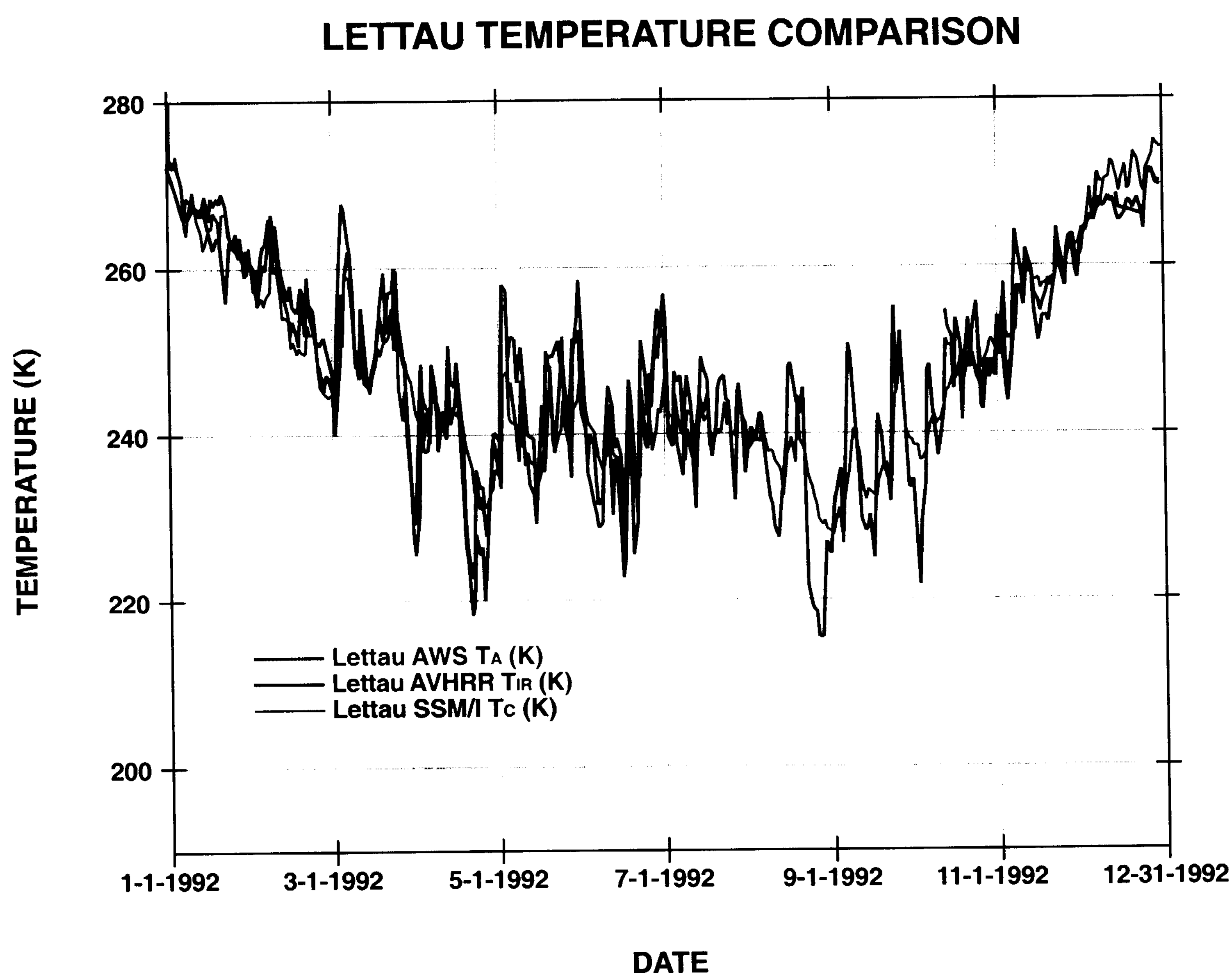

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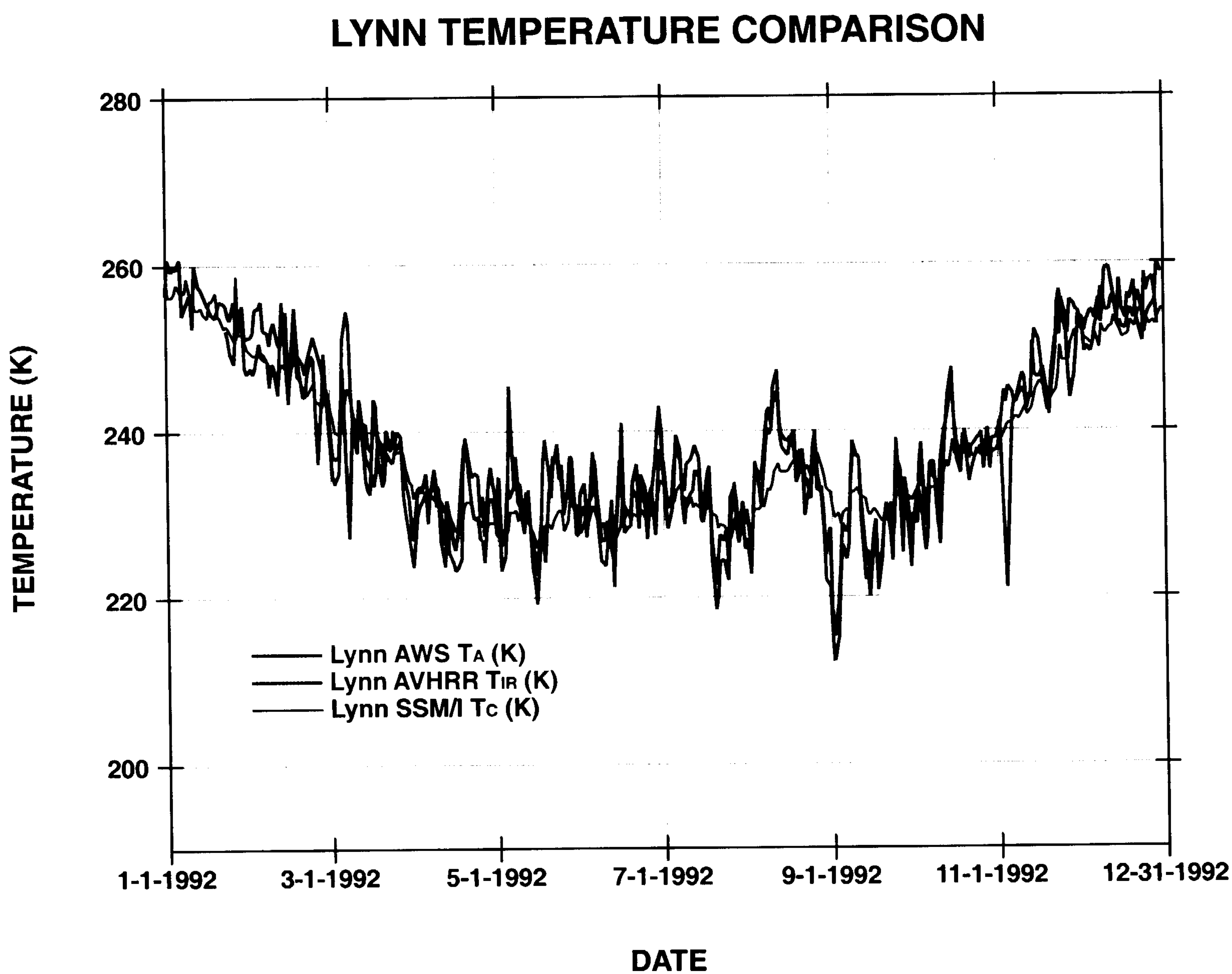

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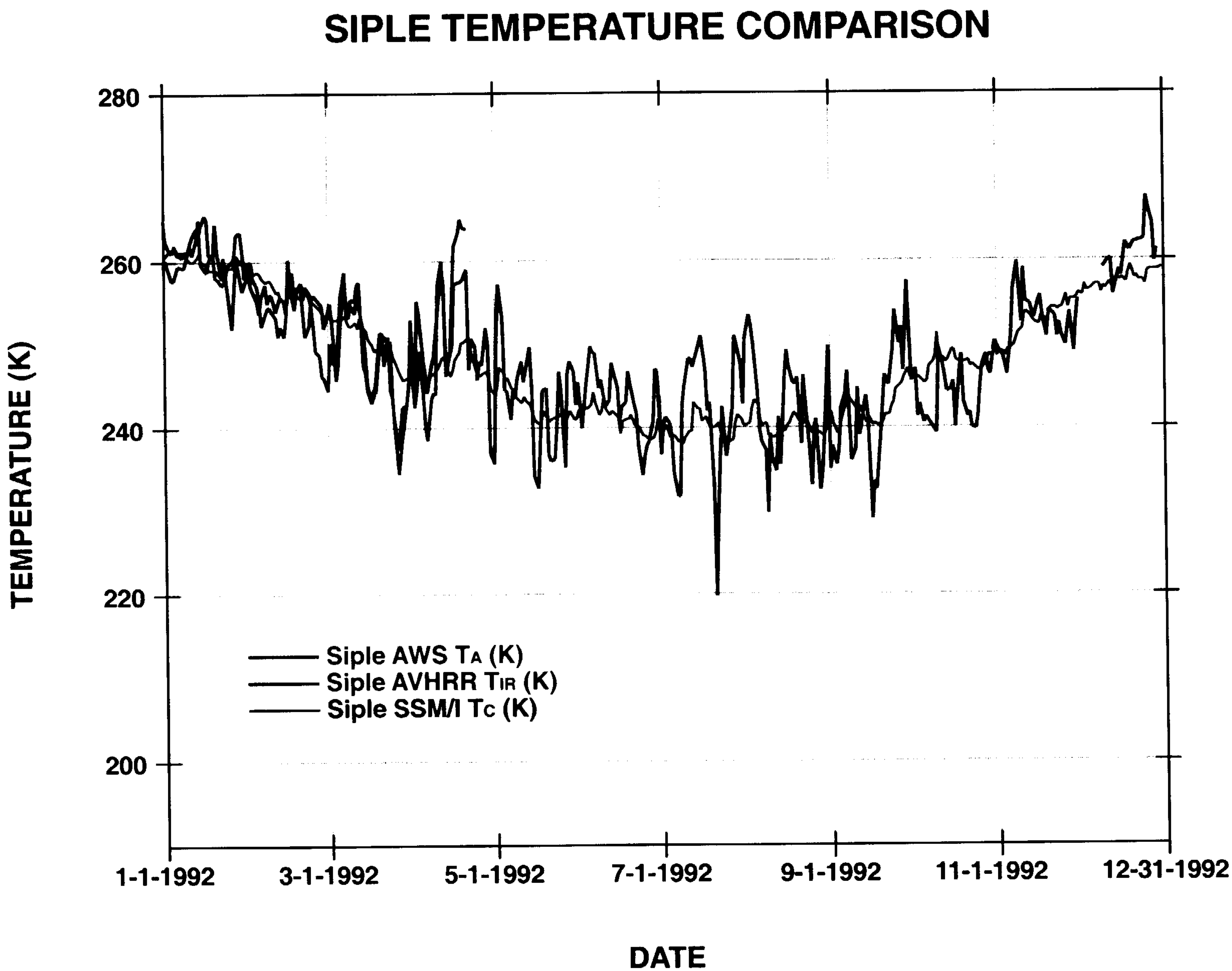

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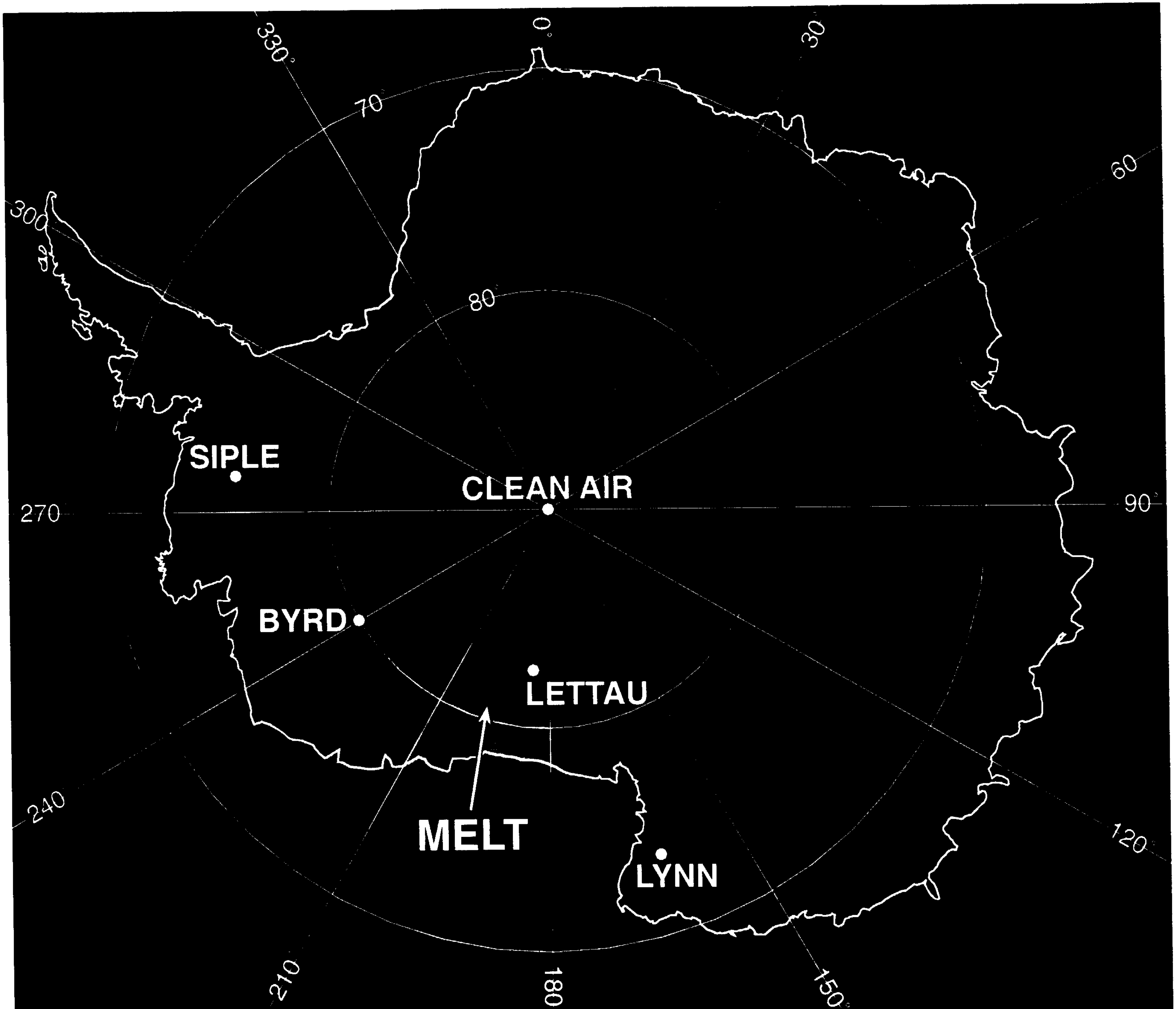

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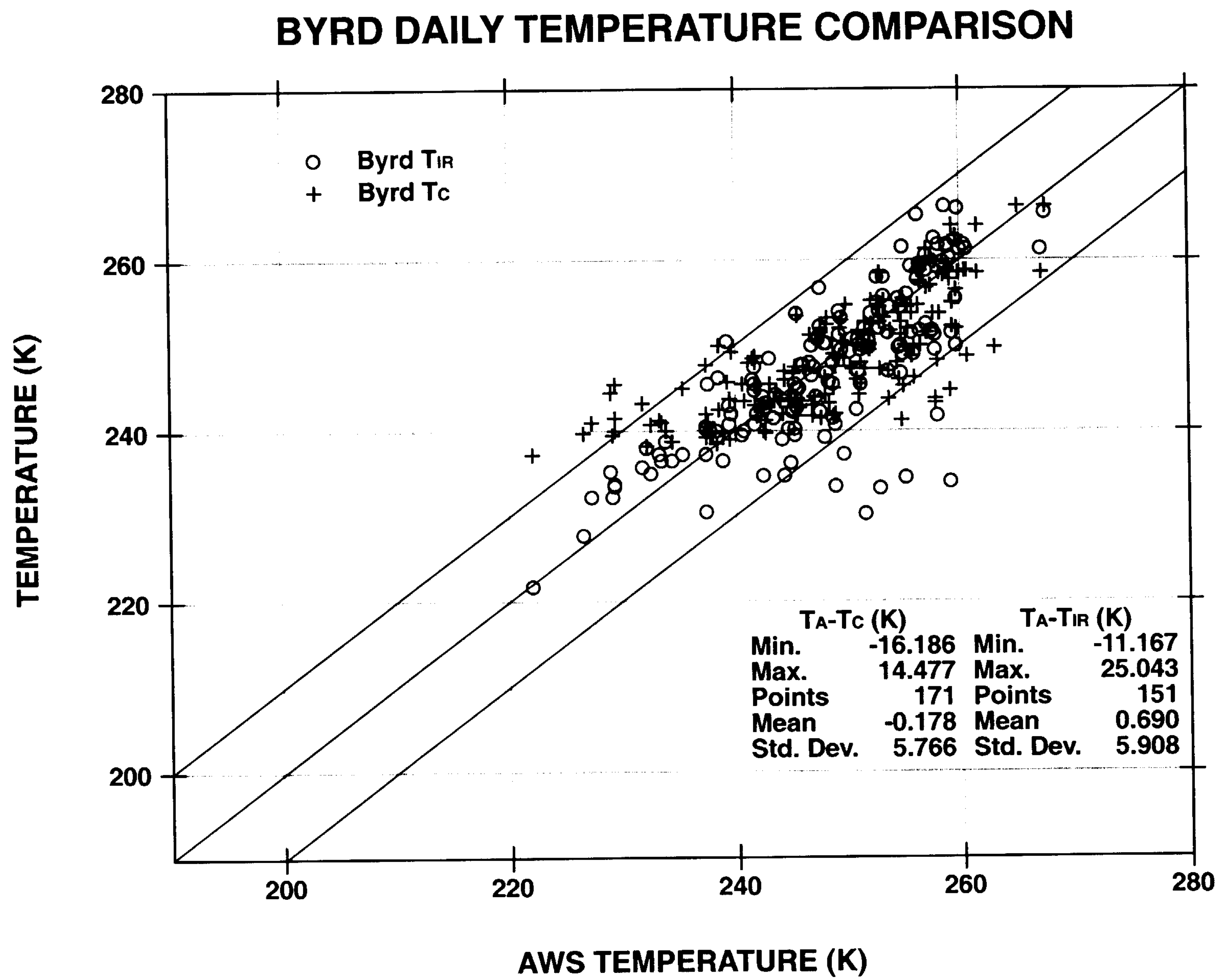

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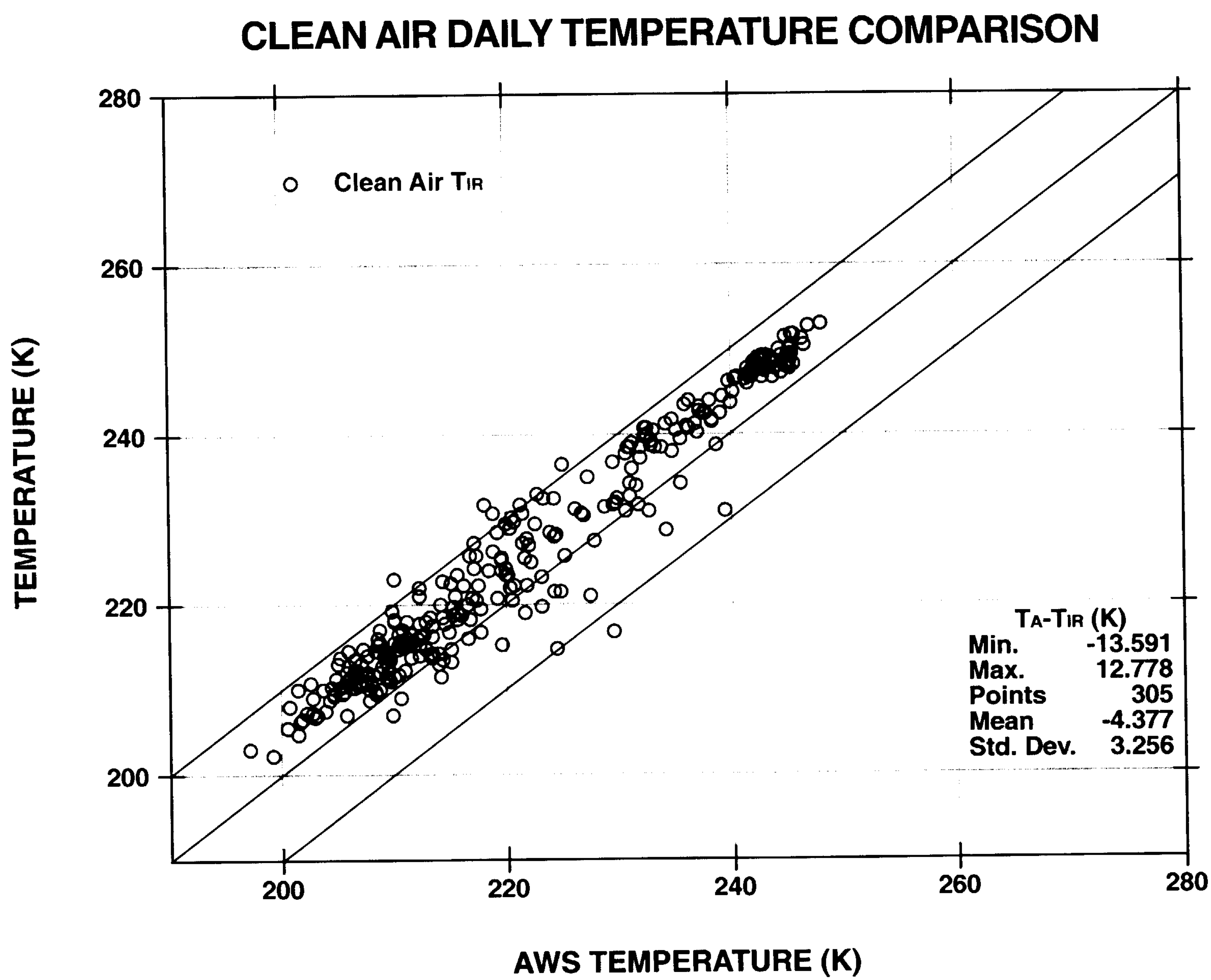

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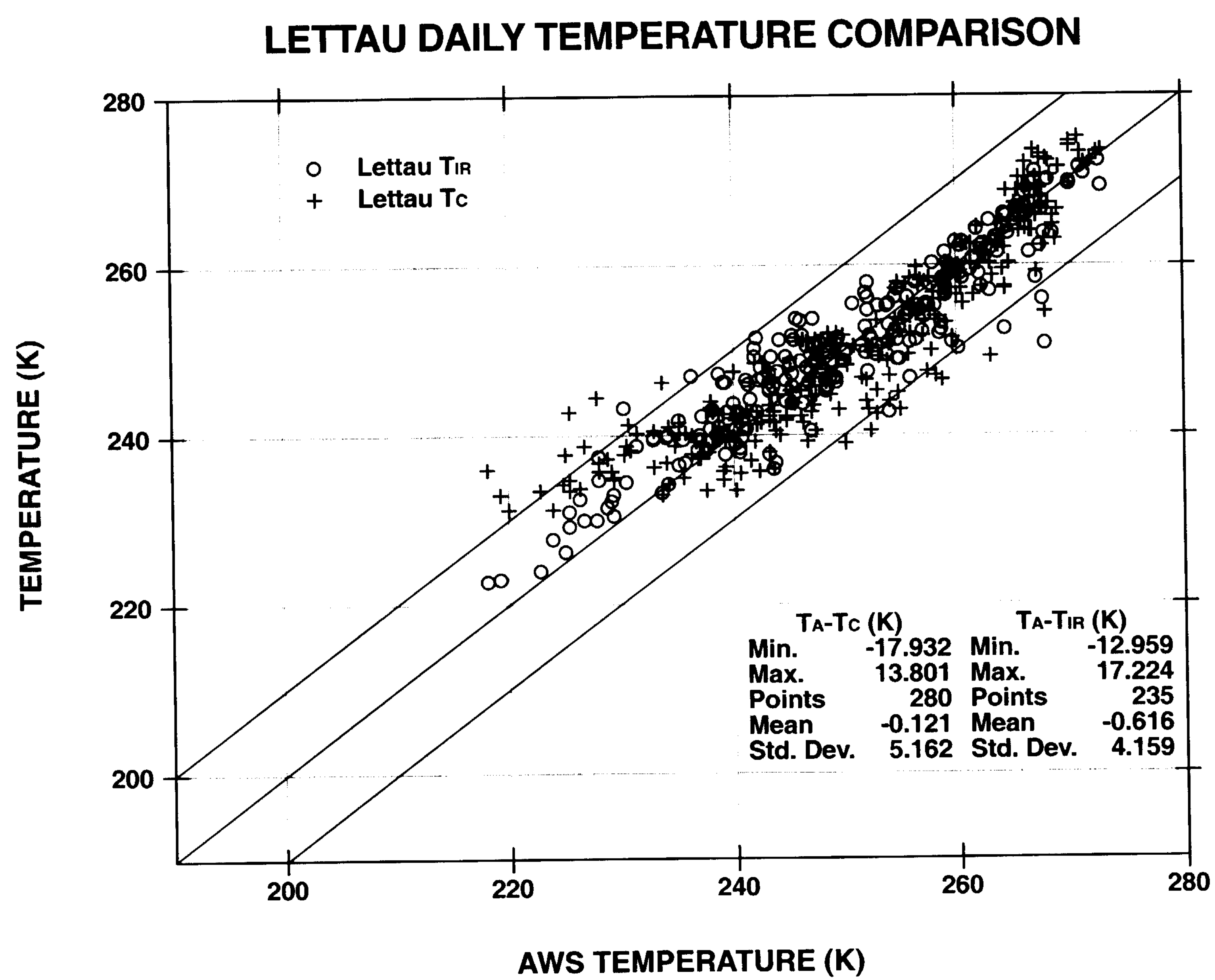

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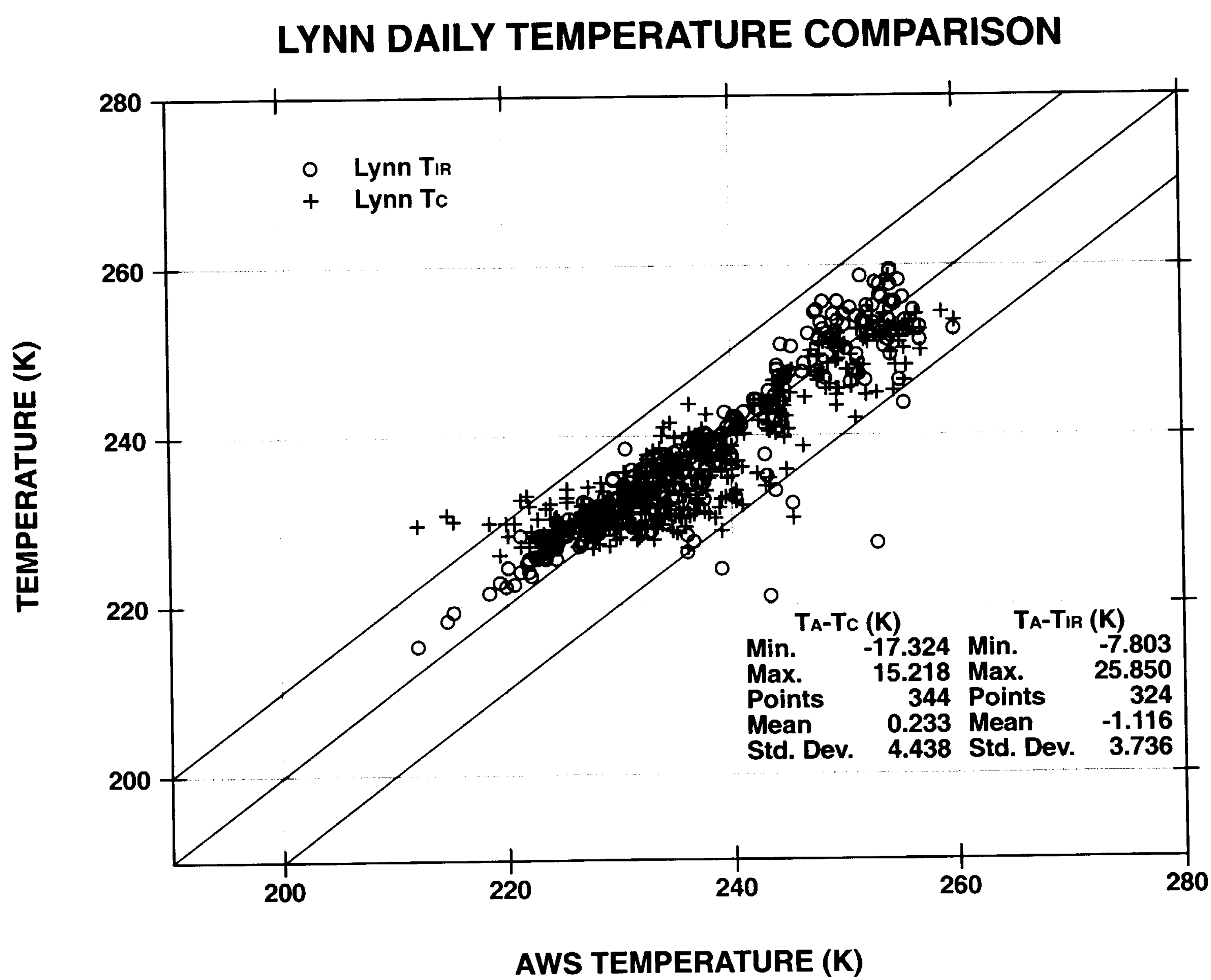

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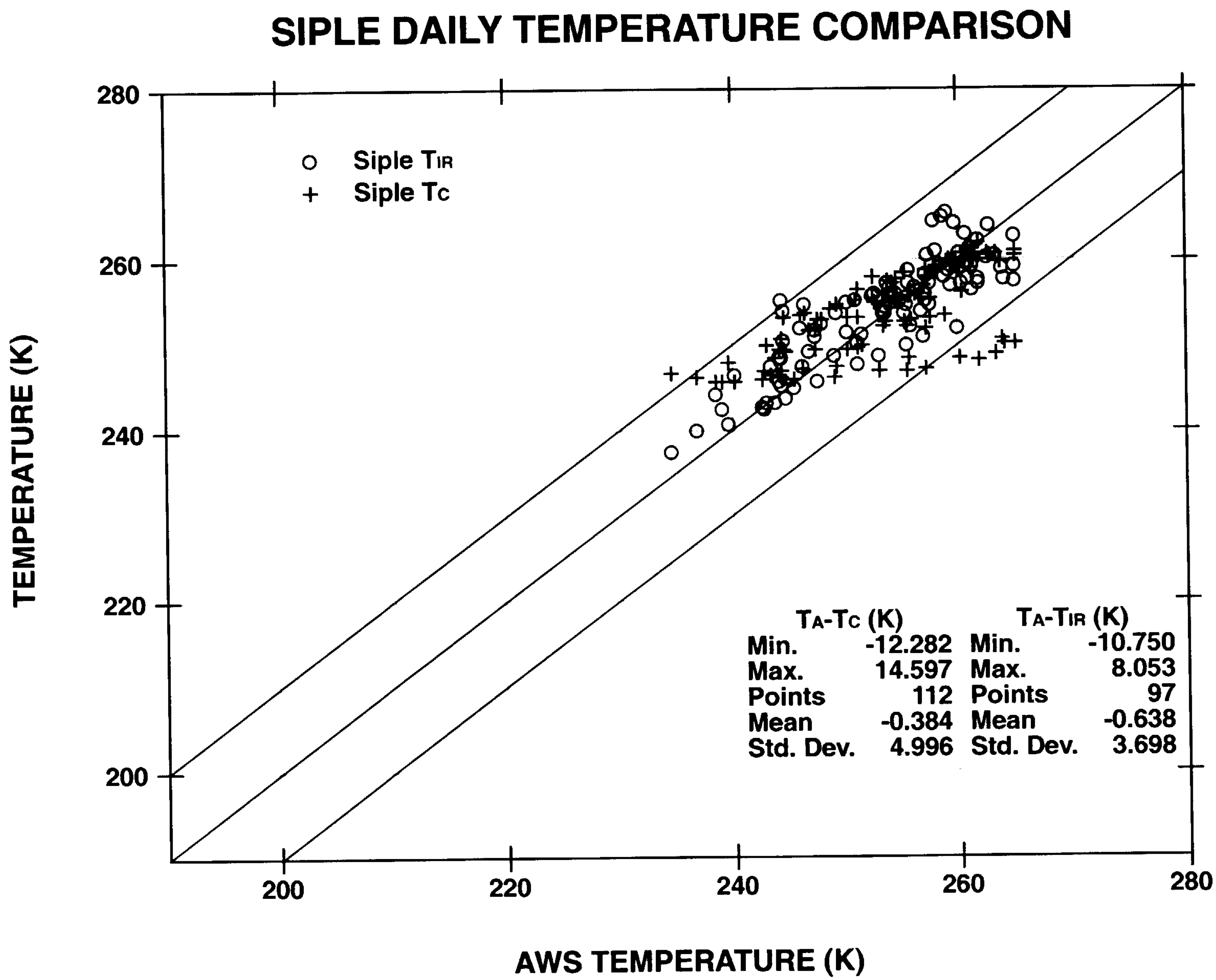

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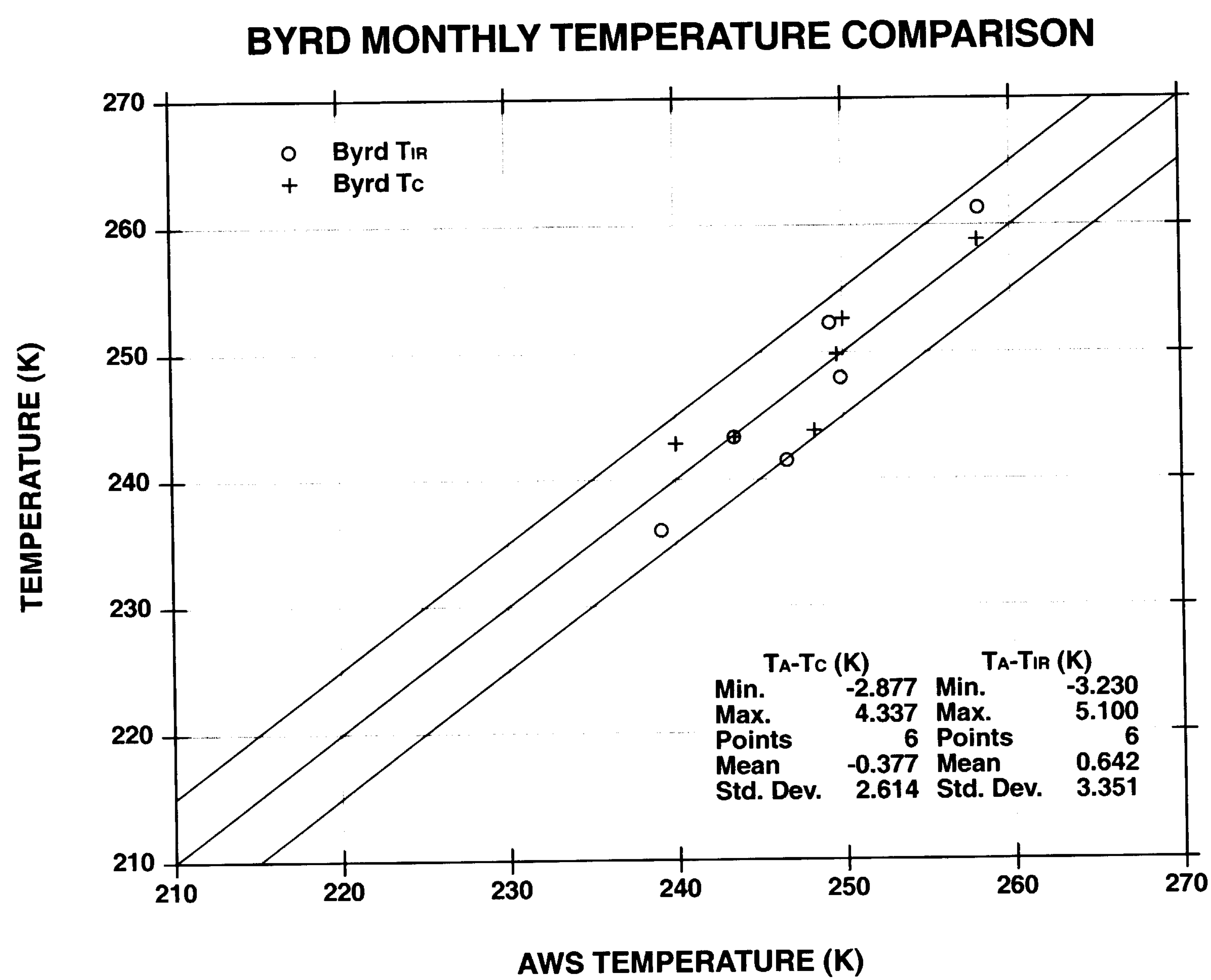

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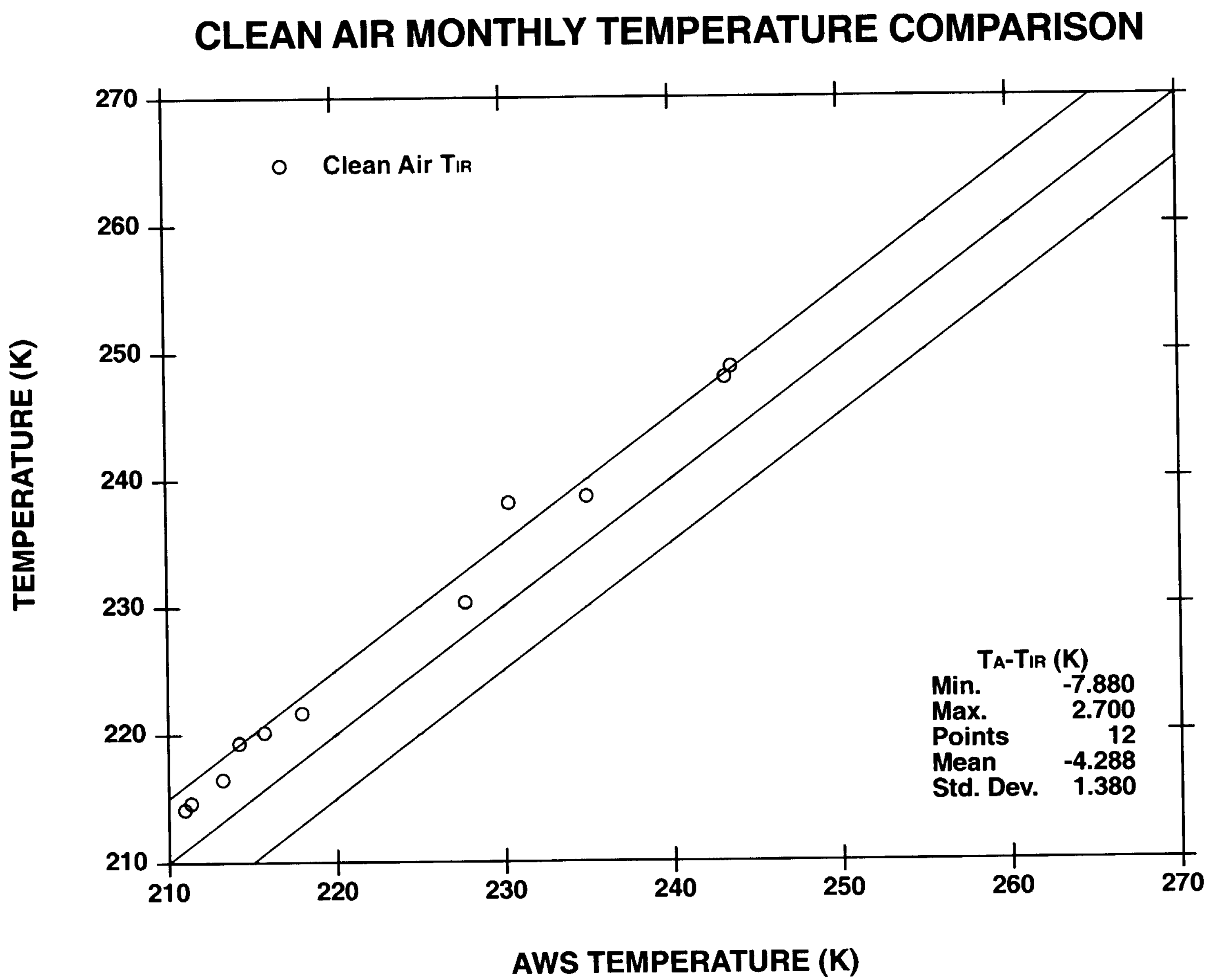

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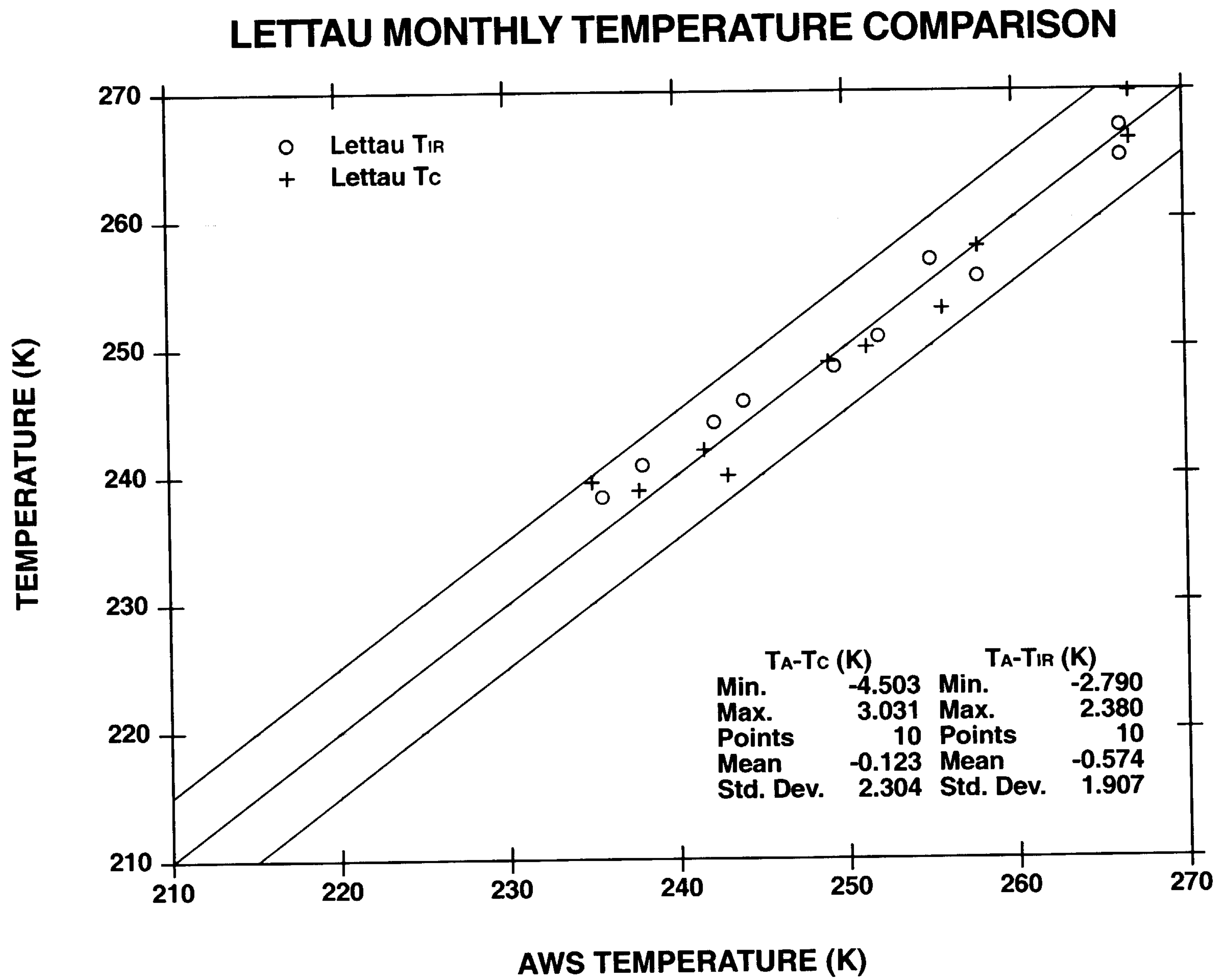

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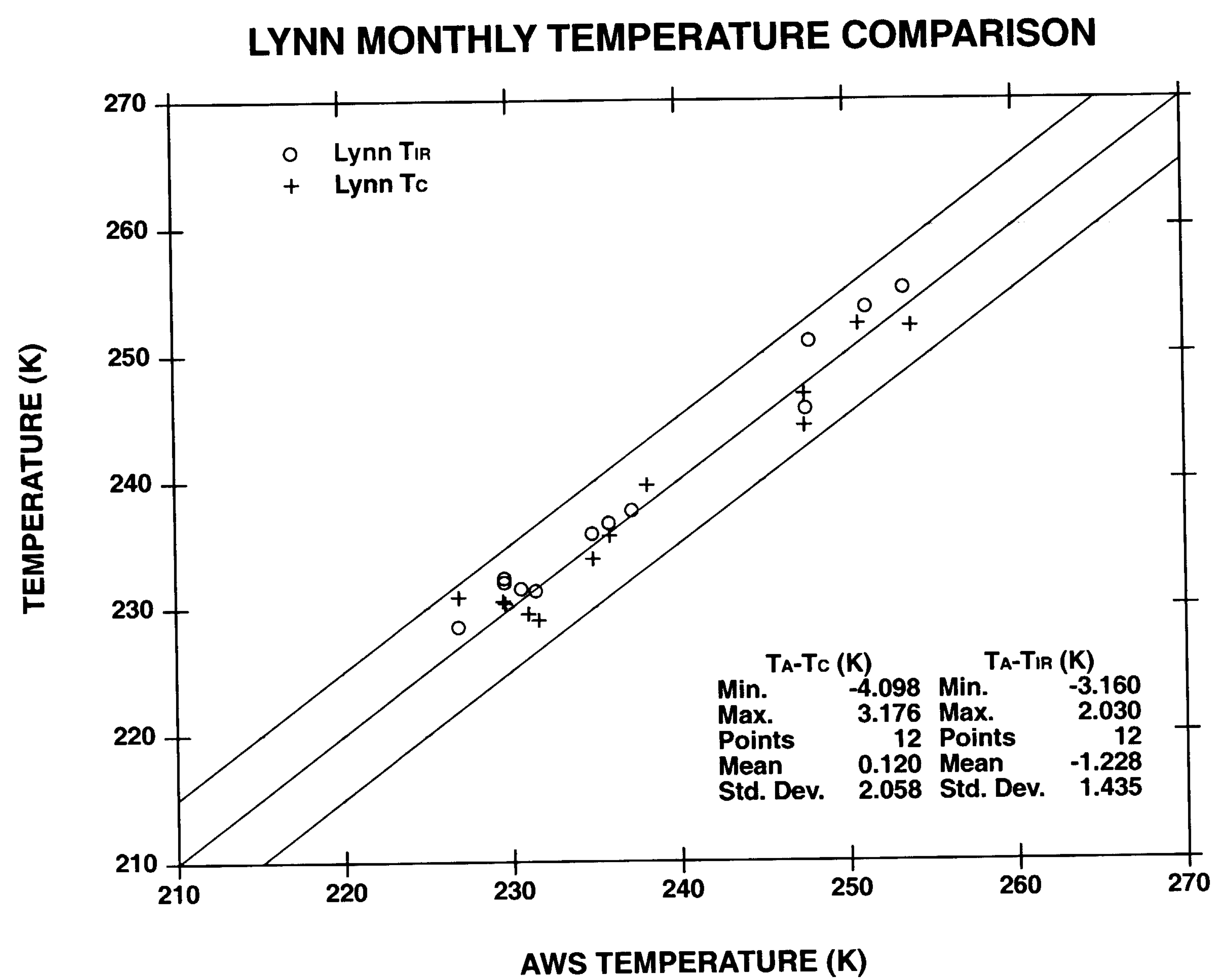

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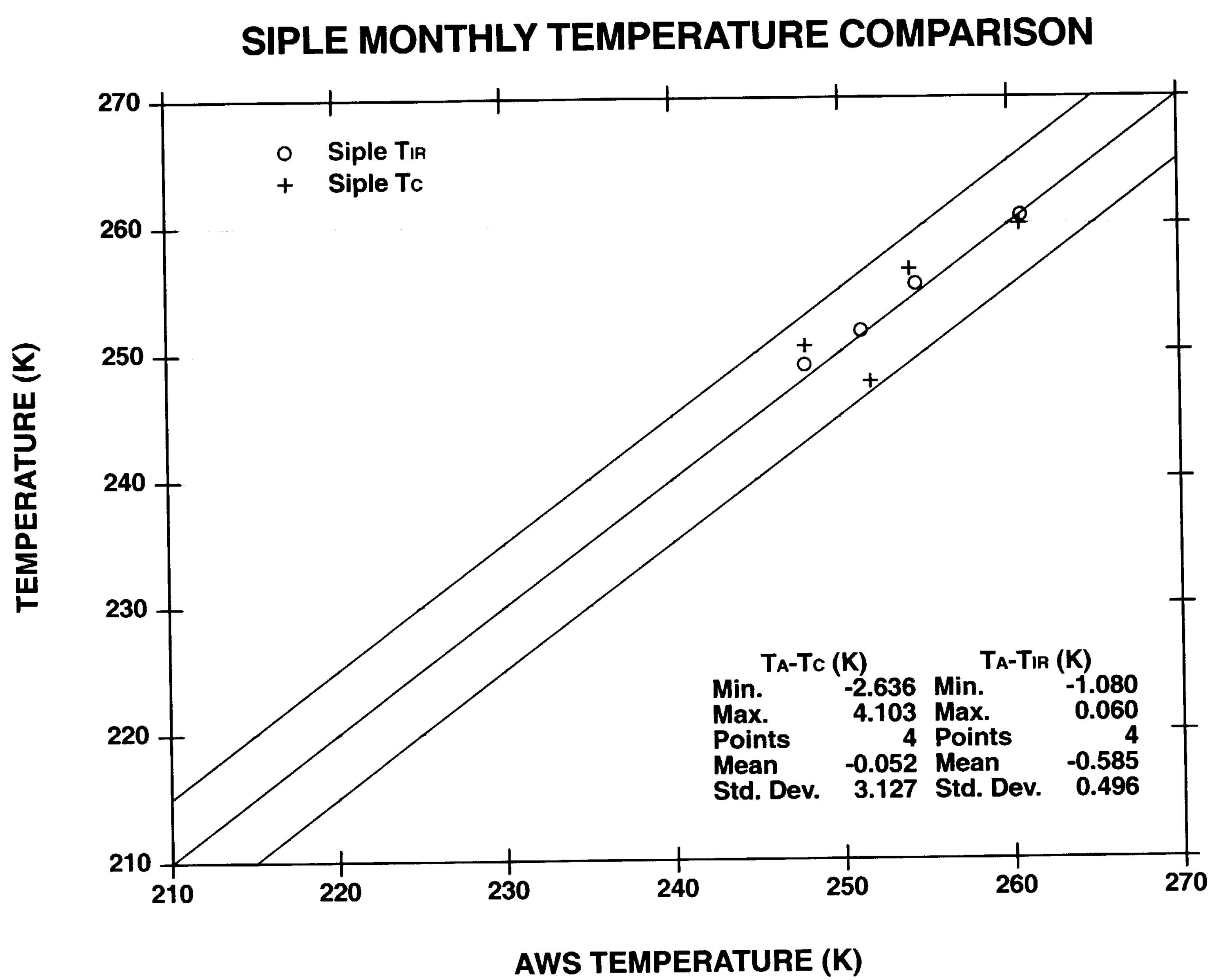

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